Brass Tacks

An in-depth look at a radio-related topic

Utah Valley
Amateur Radio Club
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Transformers

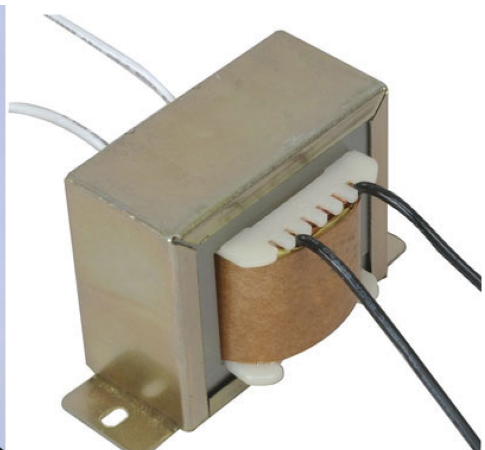
In 1831, Michael Faraday (and independently in 1832, Joseph Henry) showed that *a changing magnetic field can induce a voltage in a nearby conductor*, today known as Faraday's Law. No pun intended, this relationship transformed the electrical world, leading to the invention of the electric motor, the electric generator, and yes, the electrical transformer. Needless to say, these devices have advanced enormous changes in manufacturing, and have played a major role in the transition between the First and the Second Industrial Revolution.

Transformers can be very large, weighing tons, to handle large voltages and currents, or very small, to be installed on circuit boards. There are also very unusual transformers for unique applications, but this discussion focuses on the types that are most commonly seen or used by radio amateurs.

Let's take a closer look at the construction of a transformer, and examine the science that goes into its function. This will help us understand better how transformers apply to us common folk, and why it might be helpful to know how they work.

Transformer fundamentals

A transformer is a passive electrical device that transfers electrical energy from one circuit to another or multiple circuits. There are many different kinds of transformers, and most of them use the same principles to achieve their magic. So, what exactly do transformers *transform*? In the world of amateur radio, we typically see two applications: transformation of voltages and transformation of impedances. But if you stop and think about the math (and we will), you can see that those are pretty much the same thing.



A transformer is nothing more than two or more *inductors* working together to transfer electrical energy between circuits. Here are a couple of transformer photos, the one on the left is that of a neighborhood (residential) transformer, which converts a high voltage coming from the power company, to house voltage. The one on the right shows a common power supply transformer that might be found in an appliance, a doorbell, a charger, or furnace.

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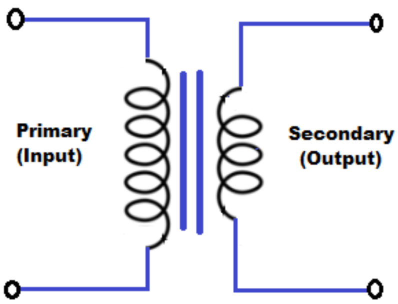
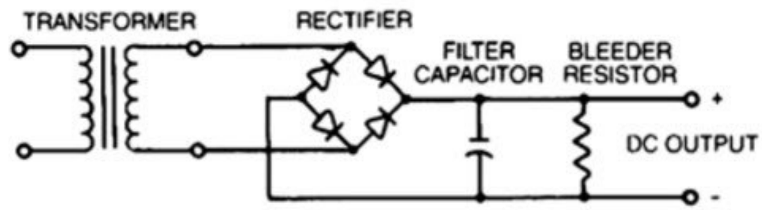
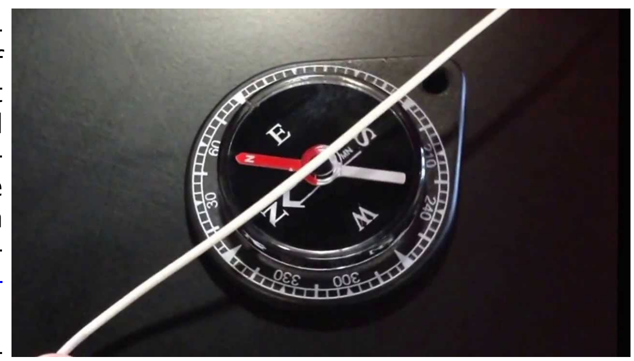
The following are two circuit schematics, the one on the left is for a transformer symbol alone, while the one on the right uses the symbol in a simple, unregulated power supply circuit:





From the transformer symbol, you can see by the two coils of wire that this one represents two inductors closely associated with each other. The lines in between the coils represent a transformer ***core***, whose material (metal, air, space, etc.) might depend on the transformer type.



You might recall that a magnetic needle compass works by pointing in the direction of Earth's magnetic field. If you send a current through a wire, it creates a magnetic field around the wire, and the influence of the magnetic field can be shown by bringing the wire next to the compass when you close the switch to complete the circuit with a battery, deflecting the compass needle. This is known as Oersted's Experiment.

Now, suppose you removed the compass, but placed a second wire next to the first one, the one you're sending current through. If you were to measure the voltage across the second wire, you would see zero volts, except when you closed and opened the switch. At the moments when your voltmeter jumps away from zero, the current in the first wire caused a voltage to appear in the second wire by means of the magnetic field, an effect called ***mutual inductance***. What this also tells you is that the current in one wire can't cause a voltage change in the next wire unless ***the current changed***.

If you were to coil the first wire in a small loop, the strength of the magnetic field created by the current in the first wire would be increased. In fact, the magnetic field strength will be multiplied by ***the number of turns in your coil***. That means the voltage jumps ***induced*** in the adjacent wire will also increase in magnitude. Furthermore, if you were to coil the second wire, as well as the first, the voltage jump across the second wire would be more pronounced.

As mentioned, the second wire only exhibits voltage when the current in the first wire changes. Suppose we make that first-wire current change constantly, like what happens with AC (alternating current). In that case, the constantly changing current in the first wire produces a constantly changing magnetic field, which then results in a constantly changing voltage in the second wire. This two-wire, mutually coupled setup is known as a ***transformer***.

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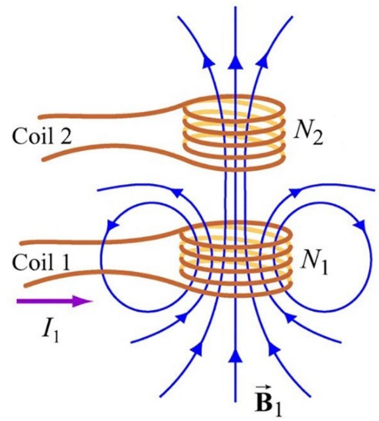
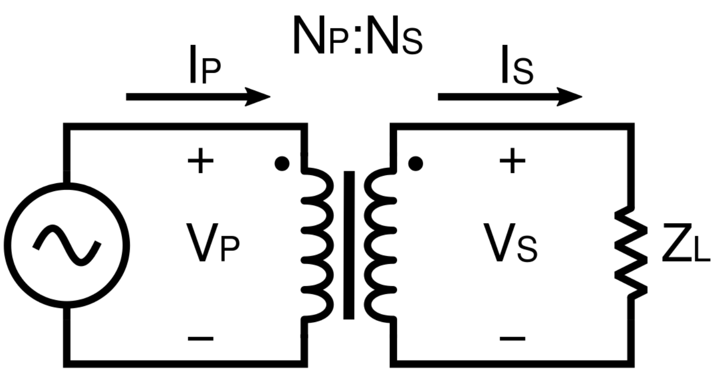
Do the math



It should be apparent that there's a mathematical relationship between the two sides of a transformer. The most foundational relationship is that ***the electrical power entering a transformer equals the electrical power exiting it***. This means that, while other properties might vary from one side of a transformer to the other, the quantity of power will be equal on both sides, simplifying many calculations.

This statement has one exception, and that is with regard to transformer ***losses***, exhibited largely as heat and flux leakage (the small part of the magnetic field that gets absorbed by something else.) Fortunately, transformer losses are quite small. But these losses are the reason that transformer efficiency is not fully 100%. For the purposes of this article, however, we will assume that transformers are ***ideal*** (and actually be very close to the truth in most low-frequency cases.)

Let's return to the original "circuit" we discussed, with a coil on one side and a coil on the other side, in close proximity with each other. Let's call the first wire the ***primary*** side of the transformer, and the second wire the ***secondary*** side. In this case, when we apply an AC voltage source to the primary side, we can call that $\mathbf{V_P}$, and its current $\mathbf{I_P}$. Therefore, the secondary side will have a $\mathbf{V_S}$ and $\mathbf{I_S}$, respectively, across a load impedance $\mathbf{Z_L}$. In addition, the number of coil turns on each side is $\mathbf{N_P}$ and $\mathbf{N_S}$, respectively. Again assuming that our transformer is ideal, we can disregard the losses for now. So, because of the conservation of energy,



$\mathbf{P_{OUT} = P_{IN}}$

$\mathbf{P_{SECONDARY} = P_{PRIMARY}}$ or $\mathbf{P_S = P_P}$

Since power is calculated $\mathbf{P = V \times I}$,

$\mathbf{V_S I_S = V_P I_P}$

Remember from our little experiment that the voltage across the secondary increased when we added more coil turns to it. In fact, the number of coil turns is proportional to the voltage on each side, meaning if our transformer has twice as many coil turns on the primary as it does on its secondary, then the voltage across the primary will be twice that of the secondary, because of the ***turns ratio***:

$\mathbf{N_P{:}N_S}$, or $\mathbf{V_P/V_S = N_P/N_S}$

And because $\mathbf{P = V \times I}$, the current is just the inverse, or $\mathbf{N_P/N_S = I_S/I_P = V_P/V_S}$

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For example

Say we have a transformer that has 500 turns for its primary winding and 250 turns for its secondary winding, tightly wrapped around an iron (actually, silicon steel) core. Say also that the primary side is plugged into the wall socket, while the secondary is connected across a 10-ohm load, like a light bulb. What are the resulting currents and voltages on both sides? We can assume that the wall socket voltage units is ***volts AC RMS*** (root-mean-square).

$V_P = 120\ \text{VAC}$, but we also know that $V_P/V_S = N_P/N_S$, so

$V_S = V_P \times (N_S \div N_P) = (120\ \text{VAC}) \times (250\ \text{turns} \div 500\ \text{turns}) = 60\ \text{VAC}$

$I_S = V_S \div Z_L = (60\ \text{VAC}) \div (10\ \text{ohms}) = 6\ \text{amps}$

$P_S = V_S \times I_S = (60\ \text{VAC}) \times (6\ \text{amps}) = 360\ \text{watts}$

$P_P = P_S = 360\ \text{watts}$

$I_P = P_P \div V_P = (360\ \text{watts}) \div (120\ \text{VAC}) = 3\ \text{amps}$

As can be seen from the above example, the transformer is converting 120 volts into 60 volts, and yet it requires only half as much current from the wall socket that the load requires. This is why your power supply can deliver 30 amps to your HF rig, but won't trip your 20-amp circuit breaker when you transmit on full power; it's likely only drawing about 3.5 amps from your wall socket, because it's presenting a much lower voltage to your transceiver.

In this case, because the secondary voltage is lower than the primary voltage, we call this a ***step-down transformer***. One whose secondary voltage is higher than the primary voltage is known as a ***step-up transformer***. (In fact, many transformers can be used to perform either function.) For our power grid, the voltages at the power plant are stepped way up (often to hundreds of kilovolts), sent across the country, then stepped back down to safer and usable levels locally.

The higher voltage in our electrical transmission lines allows for lower current to be transferred through the long, resistive wires, reducing energy lost as heat, known as ***I^2R loss***. This arises from the equations **$P = V \times I$** and **$V = I \times R$**, making **$P = (I \times R) \times I = I \times I \times R = I^2R$**.

Transforming impedances

When you set your transceiver output power to a specific level, typically your intention is to send as much of that power as possible through your antenna and into the air. The most amount of that power that you can transfer from your radio and through your antenna is known as maximum power transfer, and can only occur if your transceiver output impedance matches that of your antenna system.

One purpose of tuners is to achieve that match, but it can also be accomplished using a transformer, which can be used to transfer electrical energy between two circuits of different impedances. When used this way, we say it's ***matching*** the two impedances, meaning it presents an impedance on the primary side, matching that of the input circuit, and another impedance on the secondary side, matching that of the circuit connected to the output.

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Many hams have enjoyed the effectiveness of using a *long wire* or *random wire* antenna, which is often employed in an *end-fed* configuration. But such a wire typically presents an impedance of 1800 ohms to 5000 ohms, depending on the band of interest, and does not allow for maximum power transfer from a 50-ohm transceiver. The goal, then, is to design a transformer with a primary impedance of 50 ohms, and a secondary impedance of between 1800 ohms and 5000 ohms.

The transformer calculation will involve determining the number of required winding turns on each side, to match the impedances on both sides, since the voltages and currents are not only unknown, but unnecessary. We start by relating the numbers of turns to impedances:

$$Z_S / Z_P = [(V_S/I_S) / (V_P/I_P)] = (V_S \times I_P) / (V_P \times I_S)$$

$$V_S = V_P \times (N_S / N_P) \text{ and } I_P = I_S \times (N_S / N_P)$$

$$Z_S / Z_P = \{[V_P \times (N_S / N_P)] \times [I_S \times (N_S / N_P)]\} / (V_P \times I_S)$$

$$Z_S / Z_P = N_S^2 / N_P^2 = (N_S / N_P)^2$$

This means the impedances relate to each other by *the square of the turns ratio*. In the case of the long wire, the square of the turns ratio is

5000 ohms / 50 ohms = 100 and **1800 ohms / 50 ohms = 36**

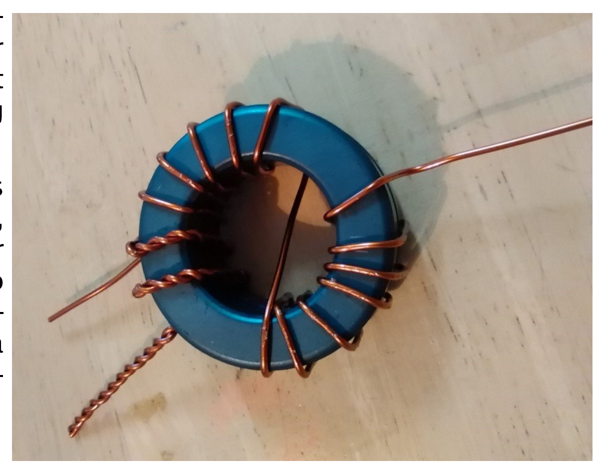
For convenience, let's select a perfect square between those values, such as 64 or 49. Selecting 49, for example, will result in standing wave ratios of

1800 ohms / 49 = 37 ohms and **5000 ohms / 49 = 102 ohms**

50 ohms / 37 ohms = 1.35:1 SWR and **102 ohms / 50 = 2.04:1 SWR**

both well within internal tuner (maximum 3.0:1 SWR) range. The required number of transformer windings are then

$\sqrt{(Z_S / Z_P)} = \sqrt{(49:1)} = 7:1$ and then wind it with 14 turns on one side and 2 turns on the other (same 7:1 ratio) to improve mutual inductance while keeping ohmic losses low (another topic for another day.) The photo to the right shows the resulting transformer prior to being attached to an enclosure.



In this RF (radio frequency) transformer, 14 turns of the wire are wrapped around the toroidal core, with seven on one side and seven on the other side, to evenly spread the magnetic field flux into the ferrite material. The 2 turns are *bifilar*, or intertwined with two of the 14, then the two share a common feed point from the antenna center conductor.

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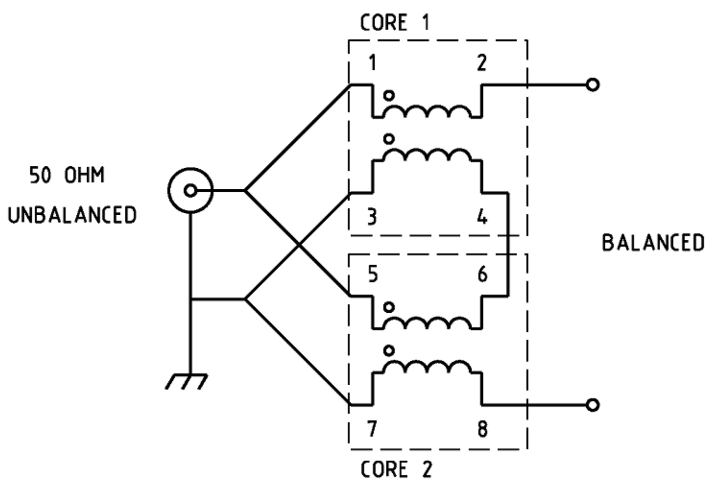
Balun transformers

A discussion about using transformers for antenna impedance-matching isn't complete without mentioning the difference between an *autotransformer* and an *isolation transformer*, both of which apply to different antenna types. An autotransformer is often made from a single winding instead of a pair of windings, or can be constructed by sharing a common winding between input, output, and ground. An isolation transformer typically contains two separate windings, to electrically (and often physically) separate the primary and secondary circuits.

A special case of an isolation transformer is the Guanella current balun (schematic to the right), often used for end-fed, long wire, and OCFD (off-center-fed dipole) antennas, which require an impedance transformation between a balanced (dipole) antenna and an unbalanced (coax) feed line. A Guanella current balun also employs two separate windings, but they share a center tap connected to ground separate from the output. The result is an *ungrounded balanced output*, which reduces common-mode current that can result in shack RF or common-mode noise.



Finally

One thing we did not investigate in this discussion is the concept of phase angle, which was omitted for simplicity. The fact is, the actual relationship is

$$P_P = P_S = V_P I_P \cos\varphi_P = V_S I_S \cos\varphi_S$$

in which φ is the phase angle between the voltage and current, taking into account the ***power factor*** through a transformer. In this case, **P** is the real power, while **V** and **I** are RMS values.

Another is transformer losses. As mentioned, most of our calculations are based upon an idealized transformer, but we're forced to consider these losses as they become more pronounced with an increase of AC frequency or an increase in power. And when used in amateur radio applications, those losses due to higher frequencies can become significant.

Summary

A transformer is a device that converts the voltages between two or more powered circuits. Many real-world transformers are nearly lossless, meaning that nearly all of its output electrical power is equal to its input electrical power. From that approximation, we can calculate the electrical parameters of a transformer quite easily. A transformer is also used to match impedances between two circuits of different impedances, to promote maximum power transfer.

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